On The Flow and Fracture of Sea Ice: The Transition from an Anisotropic Continuum to a Granular Medium

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Award No. N00014-00-1-0225

LONG-TERM GOALS

To understand the physical processes underlying the inelastic deformation of sheets of first-year sea ice, with the aim of improving sea ice models.

OBJECTIVES

To understand the transition from continuum-like brittle compressive failure to granular-like sliding along sliplines/shear faults, and to formulate the sliding condition in terms of a physically-based failure criterion.

APPROACH

An experimental approach is being taken. It is guided by the hypothesis that sliding commences when Coulomb's criterion is satisfied; viz. when

$$\tau = \tau_0 + \mu\,\sigma_n$$

where τ and σ are the shear stress and normal stress acting along and across the sliding (i.e., fault) plane, respectively, τ_0 is a measure of cohesion along the fault plane, and μ is a friction coefficient. The experiments are being performed on S2 ice which is grown in the laboratory and then biaxially compressed across the columnar-shaped grains under proportional loading using a true multiaxial press housed within a cold-room. The material simulates the kind of ice from which first-year sea ice covers are made, and the loading simulates wind-induced biaxial stress states. Shear faults are introduced into test specimens by deforming virgin material to terminal failure under moderate confining stresses. Subsequently, deformation continues by sliding across the fault. Measurements are being made of the sliding stresses. The experiments are being performed by Graduate Research Assistants Erik Russell and Daniel Iliescu, under the PI's direction.

WORK COMPLETED

The study has been initiated, procedures have been established, and a first set of results has been obtained. Prior to making the measurements, the loading system was recalibrated.

Report Documentation Page

Form Approved
OMB No. 0704-0188

1. REPORT DATE **SEP 2000**	2. REPORT TYPE	3. DATES COVERED **00-00-2000 to 00-00-2000**

4. TITLE AND SUBTITLE **On The Flow and Fracture of Sea Ice: The Transition from an Anisotropic Continuum to a Granular Medium**	5a. CONTRACT NUMBER 5b. GRANT NUMBER 5c. PROGRAM ELEMENT NUMBER
6. AUTHOR(S)	5d. PROJECT NUMBER 5e. TASK NUMBER 5f. WORK UNIT NUMBER
7. PERFORMING ORGANIZATION NAME(S) AND ADDRESS(ES) **Thayer School of Engineering,Dartmouth College,,Hanover,,NH,03755**	8. PERFORMING ORGANIZATION REPORT NUMBER
9. SPONSORING/MONITORING AGENCY NAME(S) AND ADDRESS(ES)	10. SPONSOR/MONITOR’S ACRONYM(S) 11. SPONSOR/MONITOR’S REPORT NUMBER(S)

12. DISTRIBUTION/AVAILABILITY STATEMENT
Approved for public release; distribution unlimited

13. SUPPLEMENTARY NOTES

14. ABSTRACT

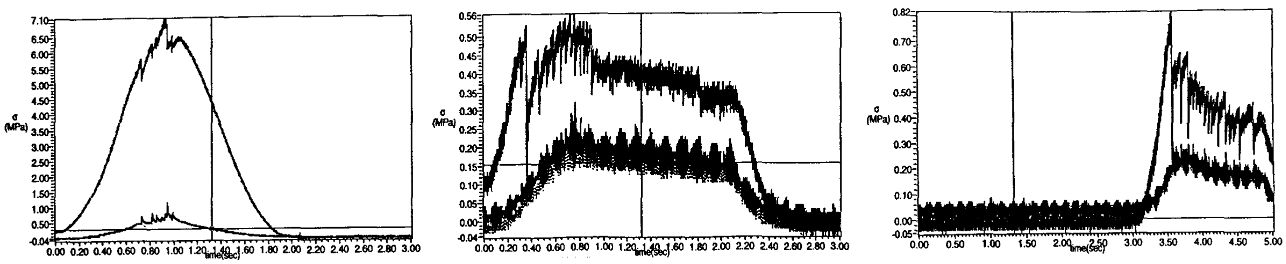
15. SUBJECT TERMS

16. SECURITY CLASSIFICATION OF:			17. LIMITATION OF ABSTRACT	18. NUMBER OF PAGES	19a. NAME OF RESPONSIBLE PERSON
a. REPORT **unclassified**	b. ABSTRACT **unclassified**	c. THIS PAGE **unclassified**	**Same as Report (SAR)**	**4**	

Standard Form 298 (Rev. 8-98)
Prescribed by ANSI Std Z39-18

RESULTS

Figure 1 shows stress-time (i.e. displacement) curves for one experiment. The upper curve denotes the major (i.e., more compressive) principal stress, σ_1, and the lower, the minor principal stress, σ_2. The specimen was composed of grains of column diameter ~7 mm and was of dimensions 150 × 150 × 25 mm (along the columns). It was biaxially loaded across columns at a displacement rate (along the major principal stress) of 0.6 mm/s. $R=\sigma_2/\sigma_1$ was ~0.1 during the fault-inducing stage, Fig.1a, and this produced a shear fault inclined by ~30° to the major axis of loading. During two subsequent sliding stages (Figs. 1b&c), R=0.3–0.4. During each of these latter stages, the "floe" above the fault was allowed to slide ~1 mm over the lower "floe" at a sliding velocity of 0.7 mm/s. "Healing' was effected between the two sliding stages, under major and minor stresses of ~0.4 MPa for 66 hours at –10°C, the temperature at which the ice was deformed. Several points are noteworthy:



a) *b)* *c)*

Figure 1. Stress-time curves for continuum (a) and granular (b, c) deformation of S2 ice.

(i) The fault formed at a terminal failure stress of 7.1 MPa (Fig.1a), in agreement with earlier measurements under the same conditions (Iliescu 2000). It was composed of a band of damage about 20 mm wide (i.e., about 3 grain diameters), again in agreement with earlier work.

(ii) Sliding occurred under much lower levels of applied stress. Upon reloading following terminal failure, sliding (Fig.1b) commenced at σ_1~0.51 MPa, and then continued at progressively lower levels of applied stress, reaching ~0.35 MPa before terminating the step. It appears to have occurred in a slip-stick manner, judging from the sudden drops in load of magnitude greater than the amplitude of the noise of the data acquisition system.

(iii) Healing increased the sliding resistance (Fig.1c). Upon reloading, after zeroing the stress after the anneal, sliding commenced at ~0.75 MPa. Again, it continued at decreasing stress levels, reaching ~0.35 MPa by the end of the experiment.

The character of sliding and the qualitative effect of "healing" were reproducible. The sliding stresses varied somewhat, however.

Video recordings revealed either little or no additional global damage during the sliding stages of deformation, at least at the level of resolution of ~0.2 mm. This implies that the inelastic deformation was confined to the damage band, in keeping with the low applied stresses.

More data are needed before Coulomb's failure criterion can be evaluated. Once obtained, they will be analyzed using the following relationship (equivalent to Equation 1) to determine whether the criterion is obeyed and, if so, to evaluate both τ_0 and μ:

$$\sigma_1 = \frac{\tau_0}{(1-R)Sin\theta\ Cos\theta - \mu\left(Sin^2\theta + RCos^2\theta\right)} \tag{2}$$

where θ is the angle between the sliding fault plane and the major stress.

IMPACT/APPLICATIONS

It is premature to make any applications of the results so far, given that too few data are available. However, with "PIPS-3.0" in mind and more data in hand, future applications will be aimed at better modeling of the deformation of sea ice sheets.

TRANSITIONS

As soon as more information has been acquired and the data analyzed, the results of the study will be transmitted to all investigators who are pursuing "PIPS 3.0" modeling.

RELATED PROJECTS

Currently in progress (31-03-00 to 30-03-01) is a study entitled, "Arctic Sea Ice Stress Array" (by Overland, Richter-Menge and Schulson, Grant no. N00014-00-1-0402). The present project will input laboratory observations to the field observations, in hopes of better understanding the latter.

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